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Special Topic: Cohesive Clustered Satellites System for 5GA and 6G Networks

Waveform cooperative communication for cohesive clustered satellite systems

Yuqi HUANG[1,2], Lin MEI[1,3*], Pengyu GAO[1], Su MA[1], Zhaopeng DU[3] & Keming YU[1,3]

[1]*Pengcheng Laboratory, Shenzhen 518055, China*
[2]*School of Electronics and Information Engineering, Harbin Institute of Technology (Shenzhen), Shenzhen 518055, China*
[3]*School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin 150001, China*

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Growing demands for integrated 6G applications expose information barriers in isolated networks, driving academic and industrial interest in distributed satellite information networks (DSIN), particularly in cohesive clustered satellite (CCS) architectures [1, 2]. Within the CCS framework, waveform design serves as a critical enabler that not only establishes fundamental physical-layer functionalities but also facilitates advanced cooperative mechanisms. Orthogonal frequency division multiplexing (OFDM) performs effectively in terrestrial networks (TN) by leveraging multipath diversity in time-invariant multipath channels. However, this advantage diminishes in CCS systems, as OFDM cannot concurrently compensate for diverse Doppler shifts originating from multiple satellites. This limitation not only constrains its applicability to omnidirectional antenna-based handheld terminals but also necessitates parallel radio frequency (RF) processing capabilities for very small aperture terminal (VSAT) platforms. Recently, emerging waveform architectures, particularly orthogonal time frequency space (OTFS) and affine frequency division multiplexing (AFDM), have developed specialized capabilities to characterize Doppler delay (DD) spread features [3, 4]. Their potential in TN with abundant multipath components aligns with the requirements for waveform cooperation in CCS systems, enabling full exploitation of diversity gains embedded in artificially constructed doubly selective channels. This study demonstrates that CCS waveform cooperation effectively improves downlink bit error rate (BER) performance while operating under frame-level synchronization constraints, thereby establishing itself as a robust communication enhancement strategy for equipment with mobility, especially handheld terminals with omnidirectional antennas.

Channel diversity based on waveform cooperation. The novel waveform designs fundamentally require near-constant propagation delay and Doppler shift throughout the frame duration to maintain operational effectiveness. While this quasi-static channel condition remains valid for TN, its applicability in low-earth orbit (LEO) satellite communication (SatCom) requires re-evaluation due to the rapid fluctuations in both relative velocity and distance.

Consider a two-dimensional geometry where the receiver is stationary at $R_E\hat{\boldsymbol{x}}$, where R_E denotes Earth's radius and $\hat{\boldsymbol{x}}$ is the unit vector along the orbital plane's x-axis. Simultaneously, the satellite's position varies with time as $R_S e^{j\omega t}\hat{\boldsymbol{x}}$, where R_S is the orbital radius and ω represents the angular velocity. The derivatives of the fading parameters are derived as follows:

$$\begin{cases} \dfrac{d\tau(t)}{dt} = \dfrac{\omega R_S R_E \sin(\omega t)}{cu(t)}, \\ \dfrac{dv_r(t)}{dt} = \dfrac{\omega^2 R_S R_E [u(t)\cos(\omega t) - \frac{R_S R_E \sin^2(\omega t)}{u(t)}]}{u^2(t)}, \\ \dfrac{d\varphi(t)}{dt} = \dfrac{\omega R_S (R_E \cos(\omega t) - R_S)}{u^2(t)} \mathrm{sgn}(\varphi(t)), \end{cases} \quad (1)$$

where $\tau(t)$ denotes the transmission delay, $v_r(t)$ represents the relative velocity, $\varphi(t)$ denotes the elevation angle, $u(t) = \sqrt{R_S^2 + R_E^2 - 2R_S R_E \cos(\omega t)}$, and c is the speed of light, respectively. Building on this, for a system operating at carrier frequency $f_c = 20$ GHz, the order of magnitude of variation over a frame duration of $T_{\text{frame}} = 10^{-3}$ s remains bounded: the Doppler shift variation $\Delta\nu$ stays below 10 Hz; the delay variation $\Delta\tau$ remains under 10^{-8} s; and the elevation angle variation $\Delta\varphi$ is less than 10^{-4} degrees. Consequently, the fading parameters exhibit quasi-static behavior within a frame, validating the prerequisite conditions for waveform cooperation (see Appendix A for detailed derivations of the formulas and supplementary visual data).

CCS systems deliver services through coordinated satellites, inherently confronting time-frequency (TF) synchronization challenges, which can result in severe performance degradation [5]. Nevertheless, waveform cooperation exhibits strong robustness against such synchronization inaccuracy. The signal relationship under quasi-static narrowband fading with synchronization time offset (STO) and

* Corresponding author (email: meilin@hit.edu.cn)

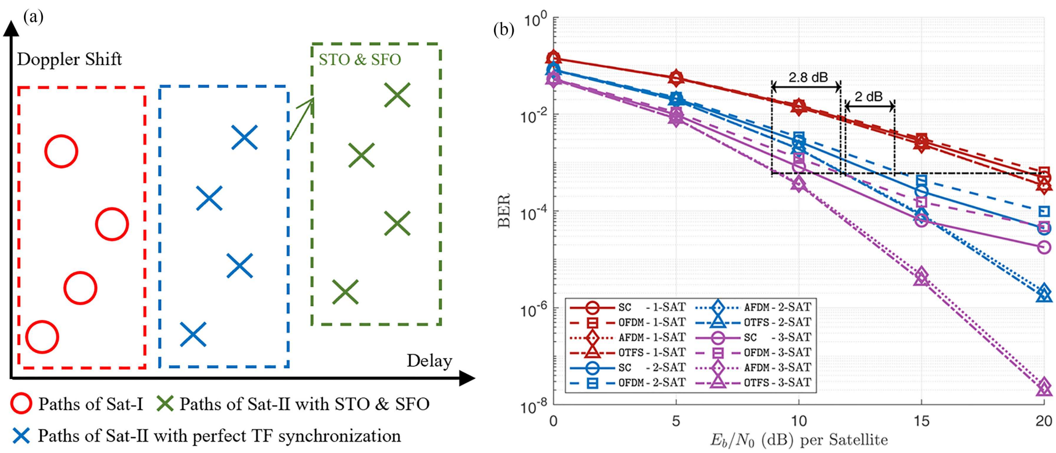

Figure 1 (Color online) (a) Impact of STO and SFO on channel diversity in a 2-SAT waveform cooperation CCS system; (b) performance gain of CCS waveform cooperation with ideal CSI, linear minimum mean squared error (LMMSE) equalization, and quadrature phase shift keying (QPSK), with paths per satellite $P_n = 2$, data length $L = 1024$ (OTFS operates at a size of delay grids $D = 32$ and Doppler grids $V = 32$).

synchronization frequency offset (SFO) satisfies

$$r(t) = \sum_{n=1}^{N} \sum_{i=1}^{P_n} \alpha_{n,i} s(t - \tau_{n,i} - T_{\mathrm{O},n}) \times \mathrm{e}^{\mathrm{j}2\pi(f_{D,n,i,} + f_{\mathrm{O},n})(t-\tau_{n,i}-T_{\mathrm{O},n})} + n(t), \tag{2}$$

where N denotes the total number of satellites, P_n represents the number of multipath components generated by the n-th satellite, $T_{\mathrm{O},n}$ and $f_{\mathrm{O},n}$ denote the STO and SFO of the n-th satellite, respectively. Additionally, the i-th multipath component from the n-th satellite experiences a delay of $\tau_{n,i}$ and a Doppler shift of $f_{\mathrm{D},n,i}$. As shown in Figure 1(a), multipath components of satellite-II simply undergo identical shifts equivalent to the STO and SFO values. As long as the shifted paths can be properly received, the waveform-cooperation system maintains channel diversity.

Experiment and analysis. Waveform cooperation offers two key benefits: it enhances the signal-to-noise ratio (SNR) and, more critically, achieves substantial diversity gain through specialized channel diversity mechanisms, as shown by the improved BER performance in Figure 1(b).

Initially, in a 1-satellite (1-SAT) configuration with limited channel diversity, all waveforms demonstrate comparable performance. In contrast, multi-satellite configurations achieve significant performance enhancement, owing to the combined benefits of SNR gain and substantial channel diversity gain. With the BER performance of OFDM at $E_b/N_0 = 20$ dB in the 1-SAT configuration as the baseline, the 2-satellite (2-SAT) scenario achieves total SNR gains of 6.1 dB for OFDM and 8.1 dB for OTFS/AFDM, demonstrating an additional 2 dB additional diversity gain. Moreover, the performance gap further widens in the 3-satellite (3-SAT) configuration, where OFDM and OTFS/AFDM attain 8.3 and 11.1 dB performance gain respectively over the 1-SAT baseline, corresponding to an additional 2.8 dB diversity gain.

These simulation results demonstrate the effectiveness of waveform cooperation, confirming that this approach enables all waveforms to attain additional diversity gains. Particularly, OTFS and AFDM achieve remarkable performance gains over OFDM in waveform cooperation, as they fully leverage the diversity offered by the CCS channel. Therefore, we advocate for adopting novel waveform designs with inherent delay and Doppler resolution capabilities in CCS systems to fully unlock the potential of waveform cooperation.

Conclusion and future work. In conclusion, strategic waveform cooperation demonstrates significant potential for enhancing BER performance through the effective utilization of channel diversity. Our future studies will focus on conducting comprehensive joint waveform-channel analyses.

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Supporting information Appendix A. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 You X H, Wang C-X, Huang J, et al. Towards 6G wireless communication networks: vision, enabling technologies, and new paradigm shifts. Sci China Inf Sci, 2021, 64: 110301
2 Xu L, Jiao J, Jiang S Y, et al. Semantic-aware coordinated transmission in cohesive clustered satellites: utility of information perspective. Sci China Inf Sci, 2024, 67: 199301
3 Deng Q, Ge Y, Ding Z. A unifying view of OTFS and its many variants. IEEE Commun Surv Tut, 2025. doi: 10.1109/COMST.2025.3542467
4 Bemani A, Ksairi N, Kountouris M. Affine frequency division multiplexing for next generation wireless communications. IEEE Trans Wireless Commun, 2023, 22: 8214–8229
5 Marrero L M, Merlano-Duncan J C, Querol J, et al. Architectures and synchronization techniques for distributed satellite systems: a survey. IEEE Access, 2022, 10: 45375–45409